

The GEANT Simulation Package and its use in Compton Telescope Design

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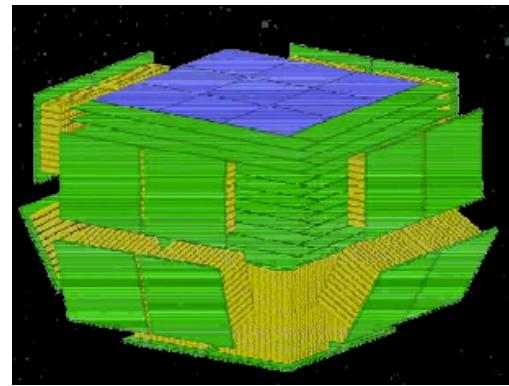
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The Role of Simulation in Design

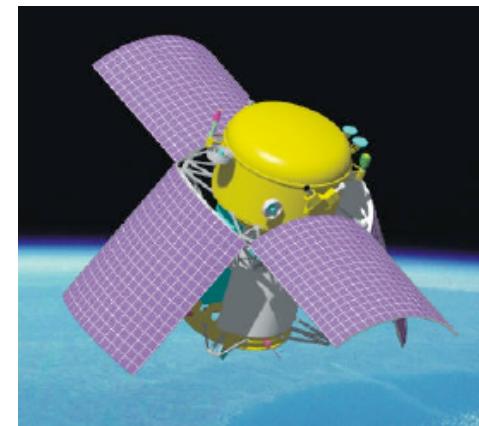
Prototypes, Balloons, etc.



Simulations, Models, etc.



Scientific Mission



MEGA Prototype

MEGA Prototype Simulation Model

MEGA Flight Concept

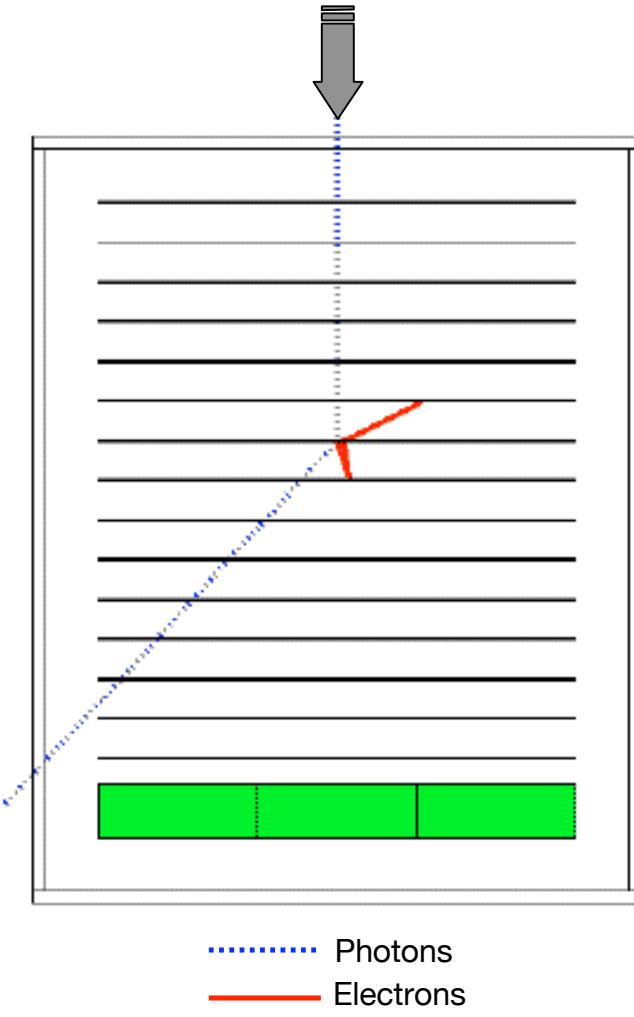
- + Realistic component performance
- ✗ Expensive and time consuming
- ✗ Inflexible configuration
- ✗ Unrealistic environment

- + Inexpensive and comparatively rapid
- + Flexible configuration
- + Flexible environment
- ✗ Must *model* the component performance

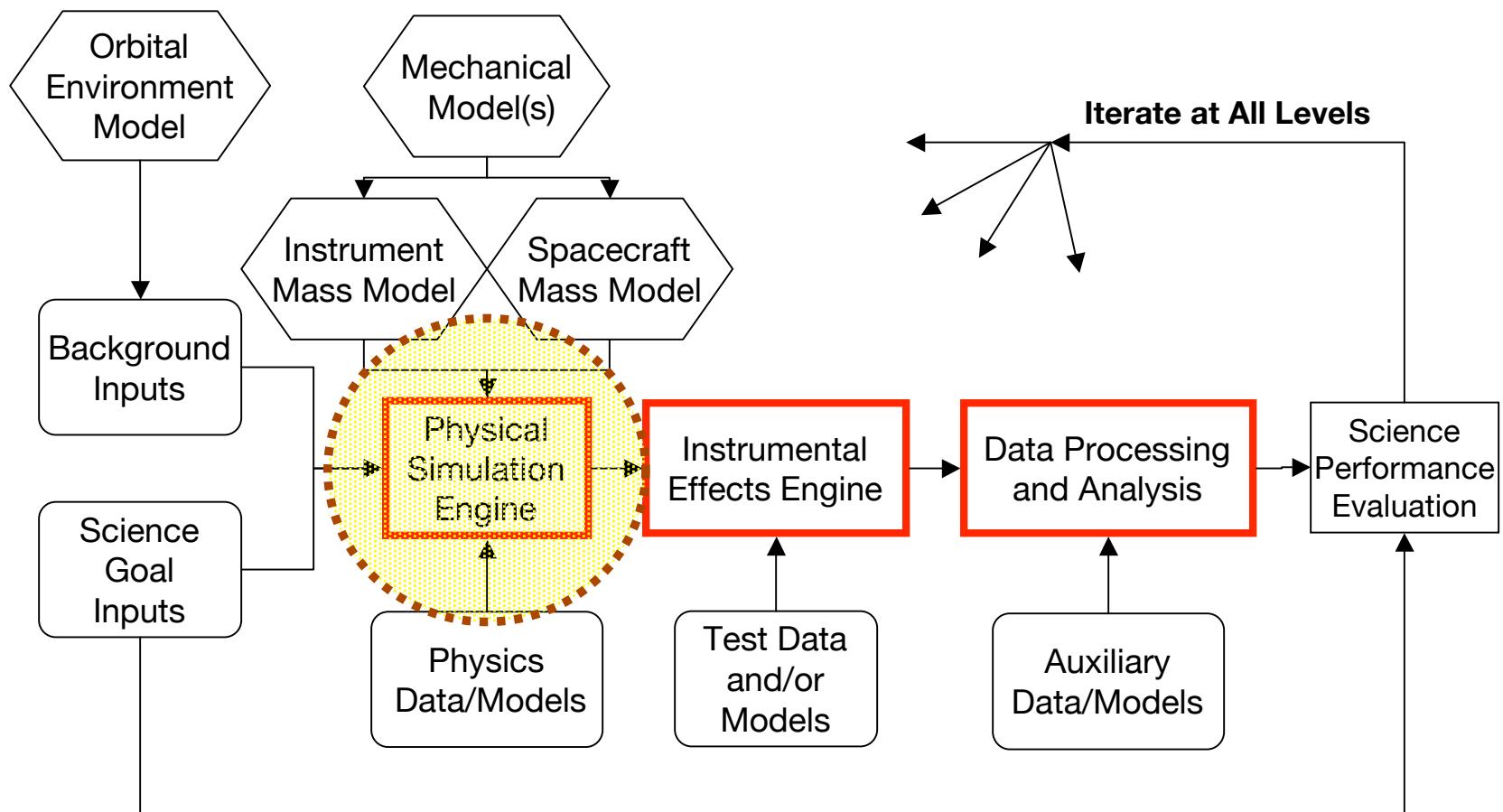
- Successful flight experiment, where:
 - Realistic estimates of performance help “sell” the mission
 - Instrument design is optimized for scientific mission and environment

Simulating Compton Telescopes

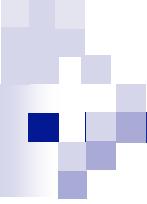
- Analytical modeling of Compton imager physical response is impractical due to complexities of geometry, scattering, and secondary production
- The most viable approach is *Monte Carlo radiation transport* simulation — probabilistic tracking individual “test particles”
- Other simulations important to instrument design: mechanical, thermal, electronics, etc.



Instrument Simulation Framework



Credible Simulation Requires Credible Inputs at All Levels



Monte Carlo Radiation Transport Packages

- Requirements for Compton Telescope simulations:
 - Detailed electromagnetic physics for direct telescope response (~1 keV – 100 MeV)
 - Competent hadronic cascade physics for simulation of prompt cosmic-ray-induced background
 - Isotope excitation and radioactive decay for simulations of delayed activation-induced background
 - Convenient and flexible handling of complex geometry and materials for rapid design studies
 - Modern, modular architecture that allows customization

- The particle and nuclear physics communities have developed several “general-purpose” Monte Carlo transport packages, including:

- EGS
- FLUKA
- HETC/MORSE/MICAP
- CALOR
- MCNP/MCNPX
- GEANT/GEANT4

Capabilities of GEANT4

geant4.web.cern.ch

- GEANT := GEometry And Tracking
- Complex 3D geometry, materials, MC transport, and visualization in one package
- Developed & maintained by CERN + large collaboration
- Modern, object-oriented (C++) “toolkit” architecture
- Comprehensive (nearly) suite of EM and hadronic physics
- Straightforward installation and use on many platforms
 - Wintel, Sun, HP, Linux, Darwin

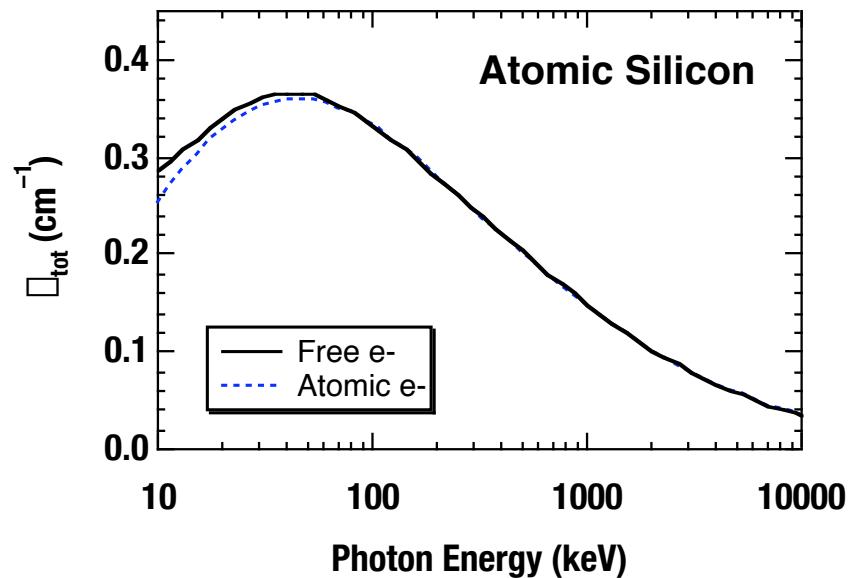
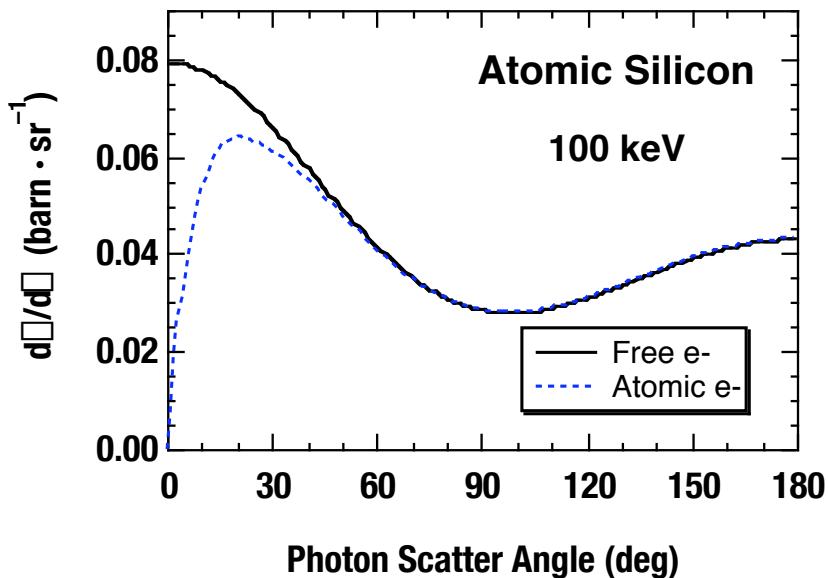
www.space.qinetiq.com

- ESA Space Specific Modules
 - General Source Particle Module
 - Toolkit for input spatial/spectral sampling
 - Radioactive Decay Module
 - Provides the capability to model activation-induced background in orbit
 - Uses detailed Evaluated Nuclear Structure Data Files
 - Low-energy EM physics
 - Uses detailed cross sections from LLNL Evaluated Photon/Electron/Atomic Data Libraries
 - Applicable above ~250 eV
 - Ties X-ray and Gamma-ray applications
- ★ **Important omission: electron binding effects in Compton**

Effects of Atomic Electron Binding

$$\frac{d^2 \sigma}{dk} = \frac{r_o^2}{4} \frac{k_f k}{k_o^2} + \frac{k_o}{k_f} \sin^2 \theta \frac{dp_z}{dk} J_i(p_z)$$

- Suppresses forward scattering, particularly at low energies
- Suppresses total scattering probability at low energies



- GEANT4 Low-energy Compton process includes these effects

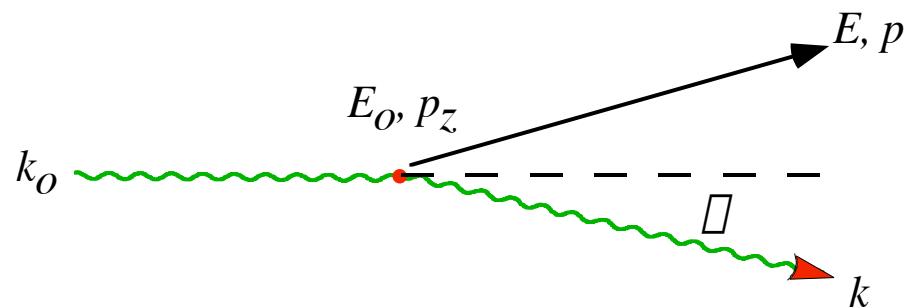
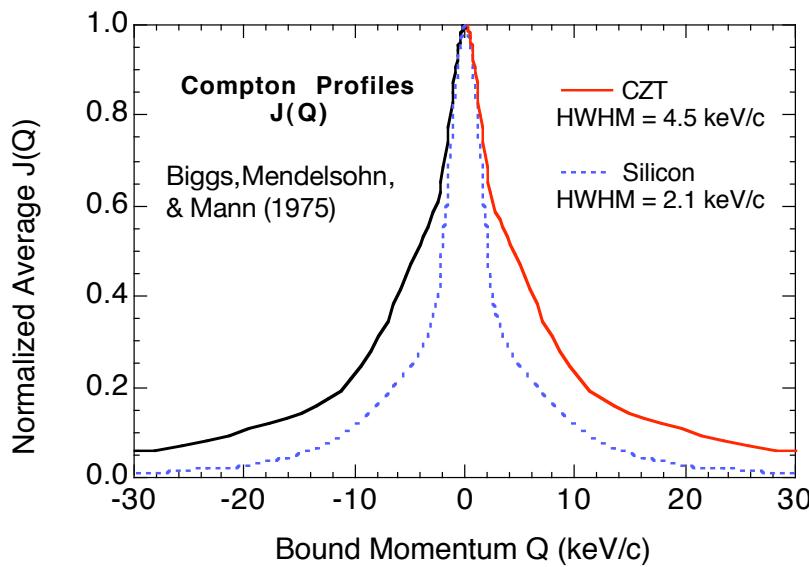
Doppler Broadening Physics & Effects

For free electron: $p_z = 0 ; E_o = m_o c^2$

$$k_{\text{free}} = k_o \sqrt{\frac{k_o k}{m_o c^2}} (1 - \cos \theta)$$

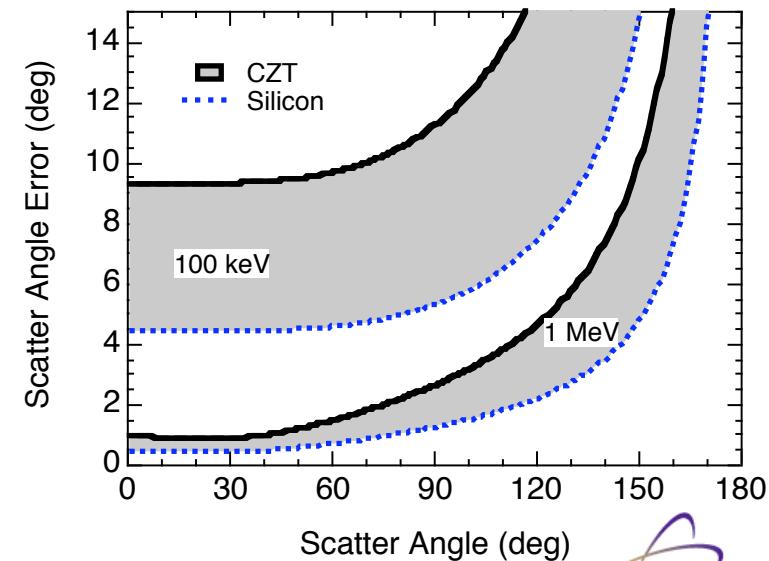
For bound atomic electron:

$$k = k_o \sqrt{\frac{k_o k}{E_o}} (1 - \cos \theta) \sqrt{p_z |\mathbf{k}_o|} \sqrt{|\mathbf{k}|}$$



Doppler broadening error:

$$\Delta k = k - k_{\text{free}} ; \Delta \theta = \theta - \theta_{\text{free}}$$





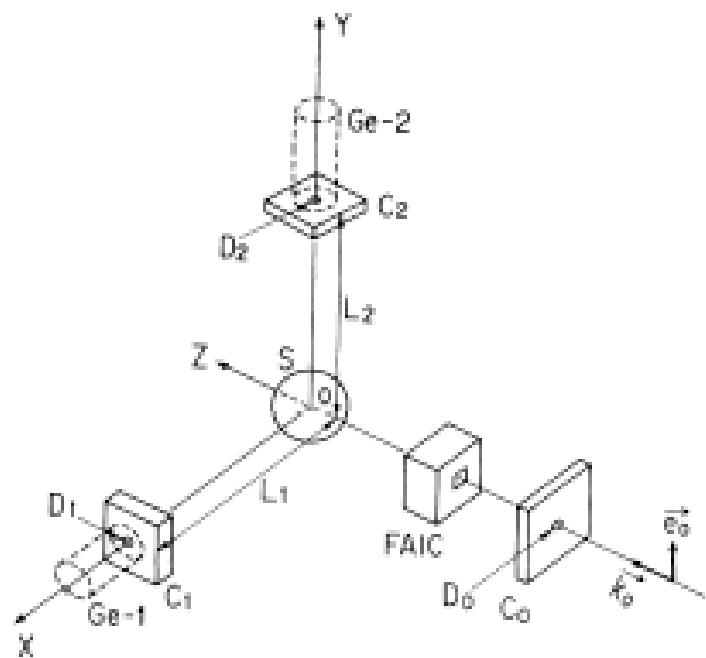
GLECS & G4LECS

- GLECS = GEANT Low-Energy Compton Scattering
 - Thanks to Doug Swartz (USRA, Huntsville) for early help
- Incorporates Doppler broadening into GEANT & GEANT4
- Algorithm based closely on EGS Implementation
 - [Namito, Ban, & Hirayama, NIM A349, 489 \(1994\)](#)
 - Relativistic impulse approximation (ignore atomic electron interactions)
 - Uses EPDL for total cross sections
 - Uses EPDL differential cross sections (scattering form factors)
 - Uses shellwise Compton profiles (Biggs, Mendlesohn, & Mann 1975) to sample Doppler broadened scattered photon energies
 - Also fixes Rayleigh (coherent) scattering physics with EPDL data
 - Computing performance within 5% of G4LowEnergy classes
- Soon to come: combined polarization and Doppler broadening

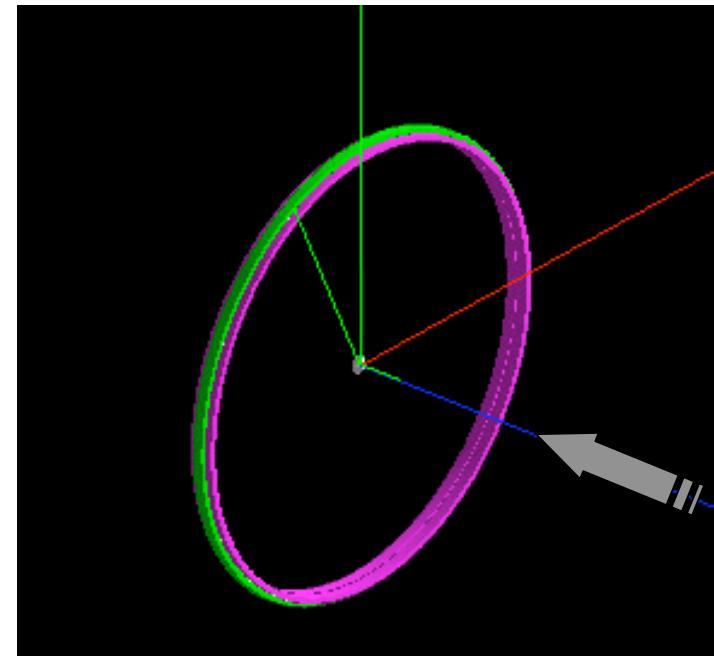


Verification of G4LECS

- G4LECS compared to synchrotron beam experiment
 - Namito, Ban, Hirayama, et al. (1994, 1995)

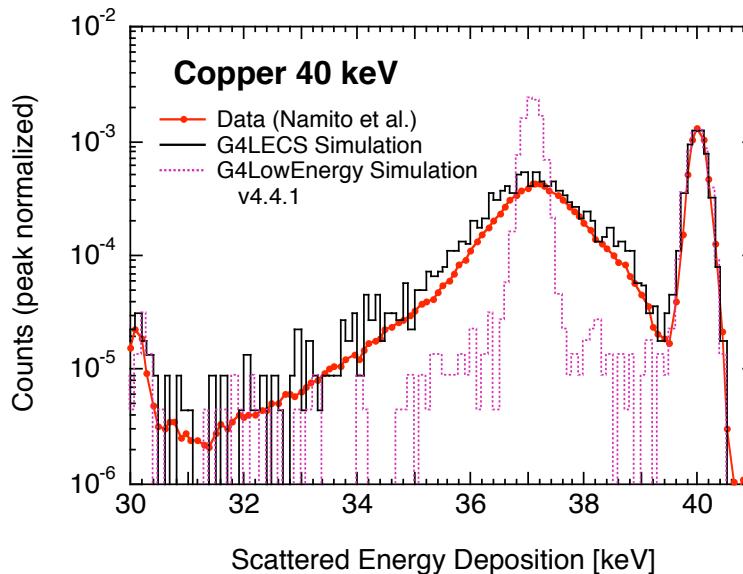
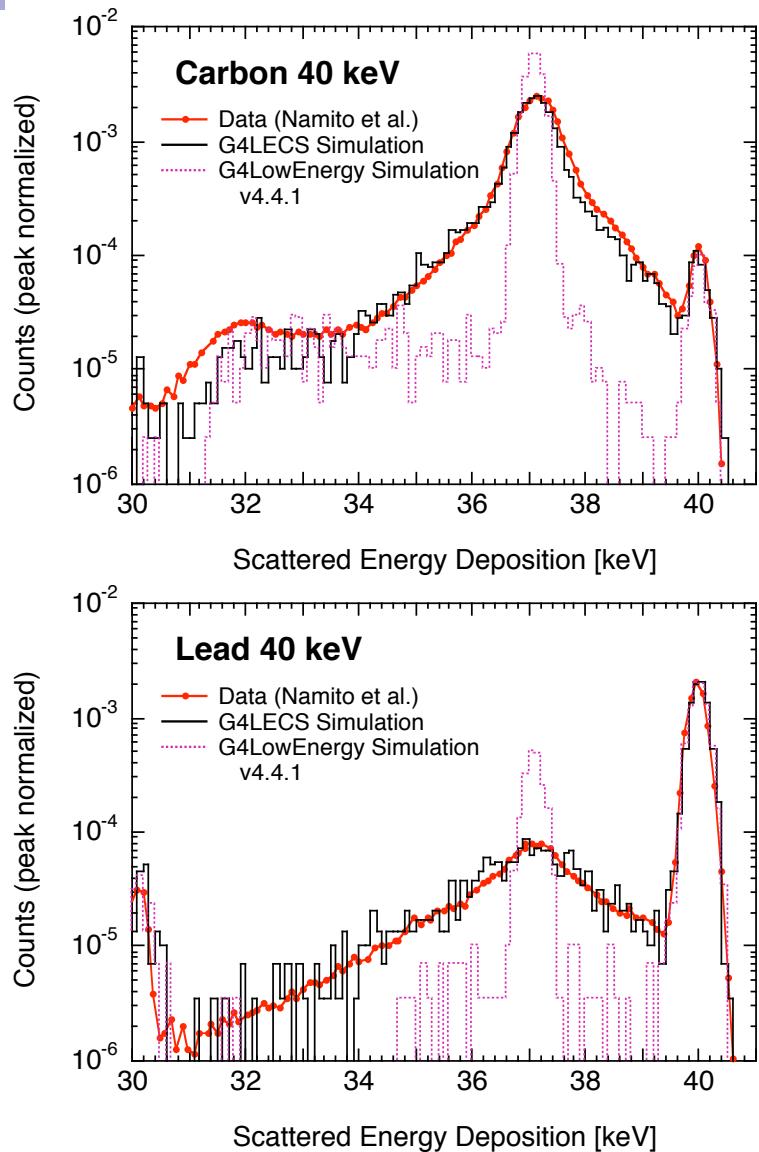


Experiment
(Polarized Beam)



Simulation
(Unpolarized Beam)

Test Results

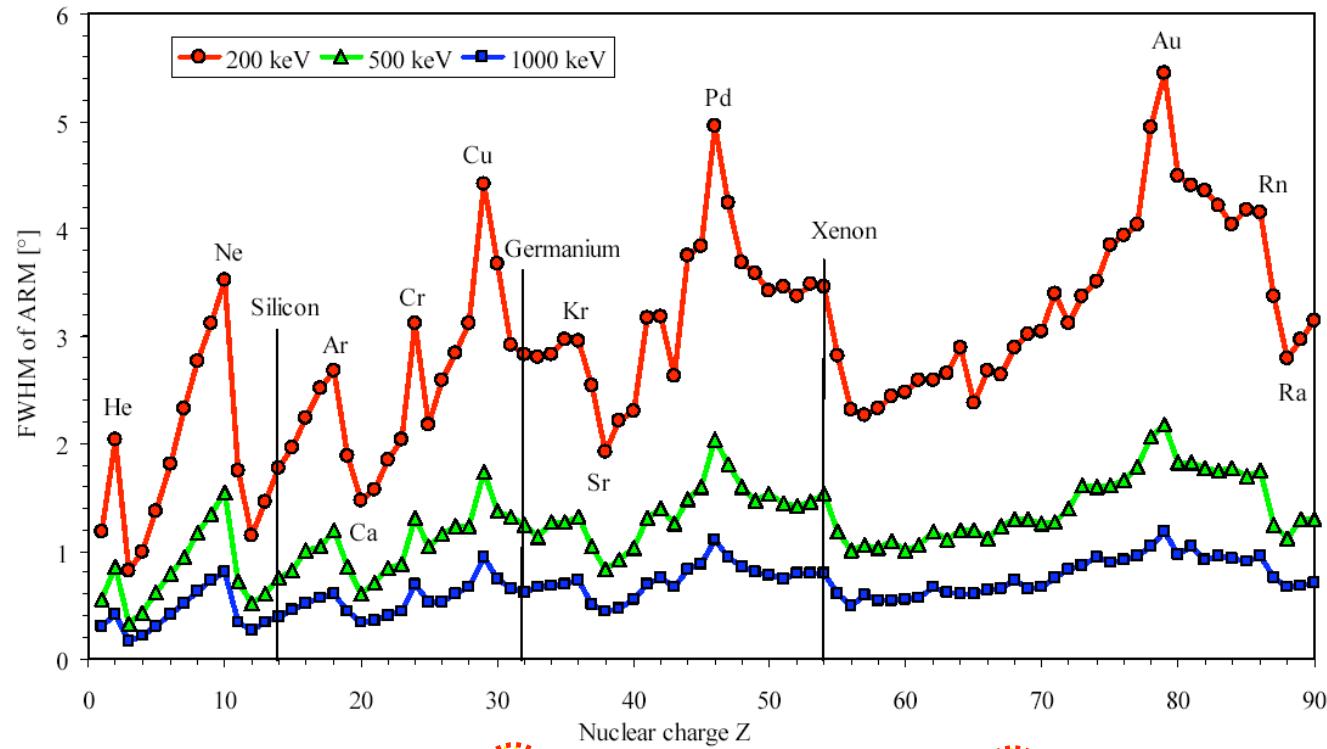


- Good agreement in Compton and Rayleigh peaks (and Ge-K escape)
- Some differences in multi-Compton continuum probably due to approximated geometry

Application to Compton Telescope Design

Doppler Limit Angular Resolution

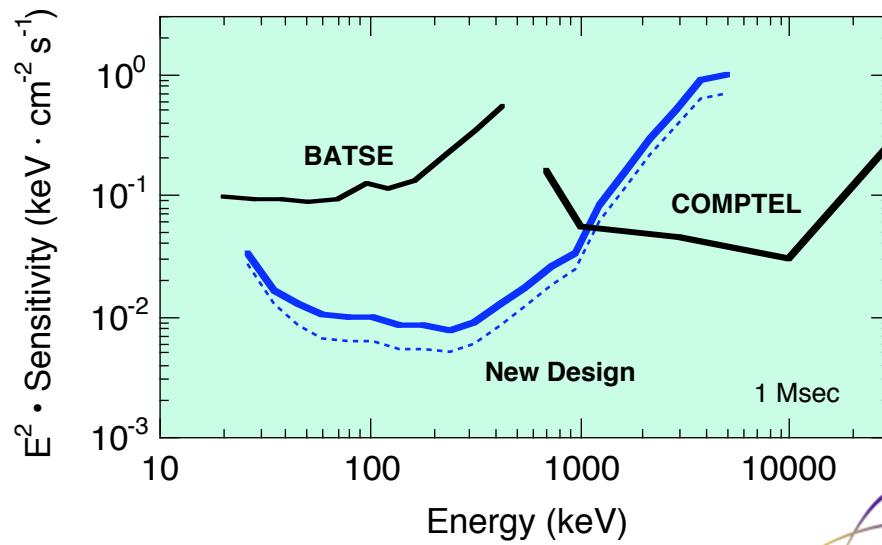
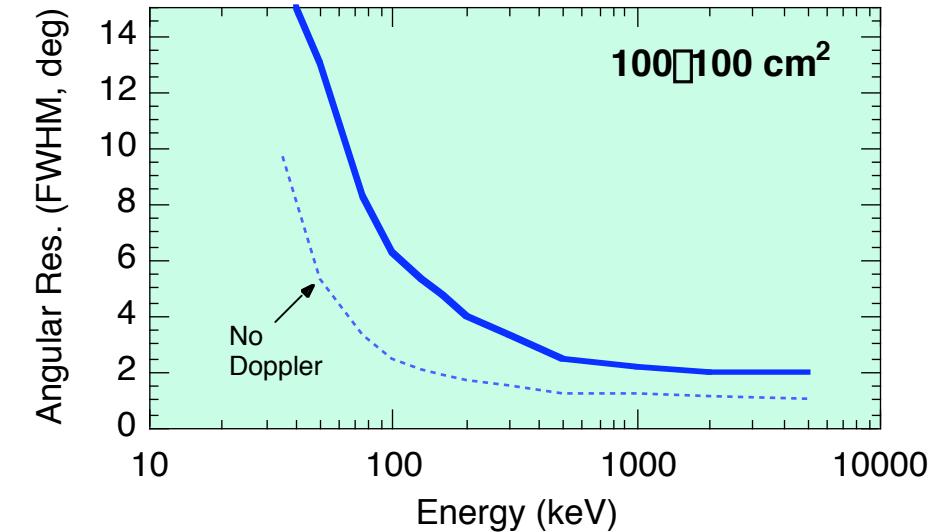
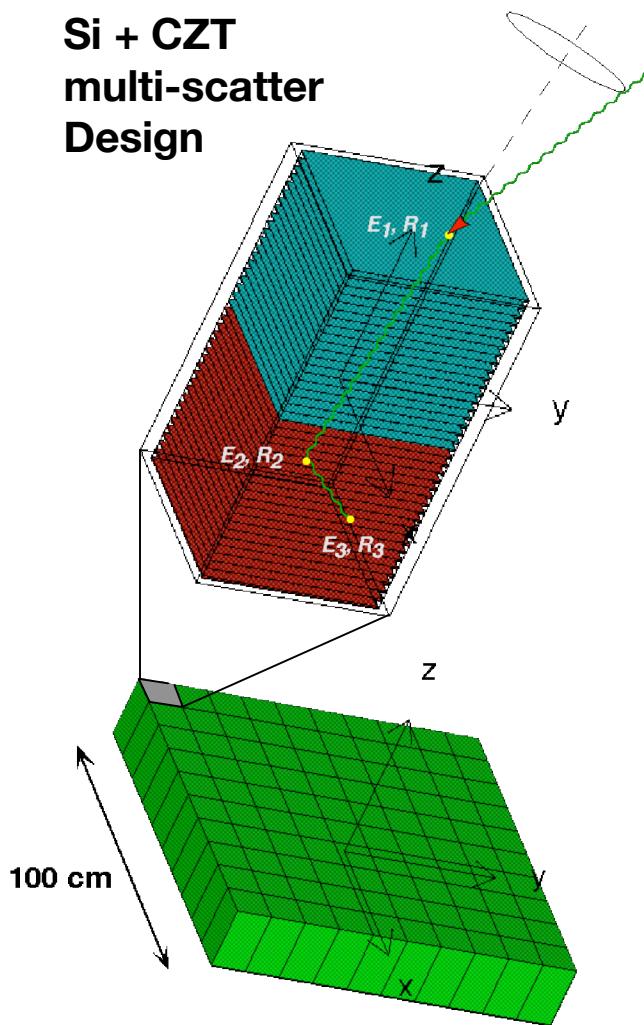
Zoglauer & Kanbach, Proc. SPIE 4851, 1302 (2003)



Material	Si	Ge	CdTe	Xe	Ne213	CsI	NaI
FWHM at 200 keV [°]	1.80	2.85	3.50	3.30	1.75	2.95	3.00
FWHM at 500 keV [°]	0.80	1.25	1.55	1.45	0.75	1.25	1.40
FWHM at 1000 keV [°]	0.40	0.65	0.85	0.80	0.40	0.75	0.85

Telescope Design Study Example

Si + CZT
multi-scatter
Design





<http://nis-www.lanl.gov/~mkippen/actsim/>
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